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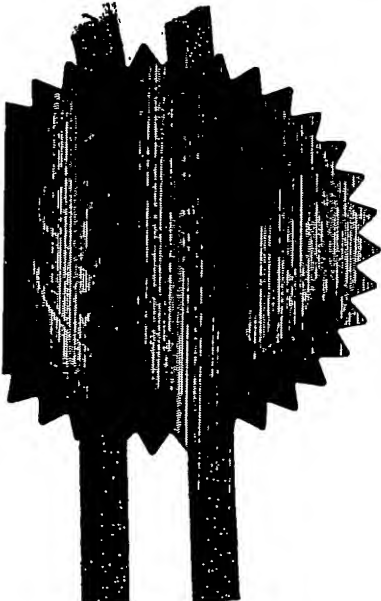
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By virtue of a direction given under Section 30 of the Patents Act 1977, the application is proceeding in the name of:

AEA TECHNOLOGY PLC,
329 Harwell,
DIDCOT,
Oxfordshire,
OX11 0QJ,
United Kingdom

Incorporated in the United Kingdom,

[ADP No. 06969372001]

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1.	Your reference	15702 MdCm
2.	Patent application number *(The Patent Office will fill in this part)*	0304192.8

25 FEB 2003

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

Accentus plc
329 Harwell
Didcot, Oxfordshire, OX11 0QJ
United Kingdom

APPLICATION FILED 6/2/04

Patents ADP number *(if you know it)*

If the applicant is a corporate body, give the country/state of its incorporation

England and Wales

8125833001

4. Title of the invention

Measurement of thermally induced stress

5. Name of your agent *(if you have one)*

Peter Turquand Mansfield

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

Accentus plc
Patents Department, 329 Harwell
Didcot,Oxfordshire,OX11 0QJ

Patents ADP number *(if you know it)*

8132243001

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Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

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11.   I/We request the grant of a patent on the basis of this application.
T. Mansfield on behalf of
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12. Name and daytime telephone number of
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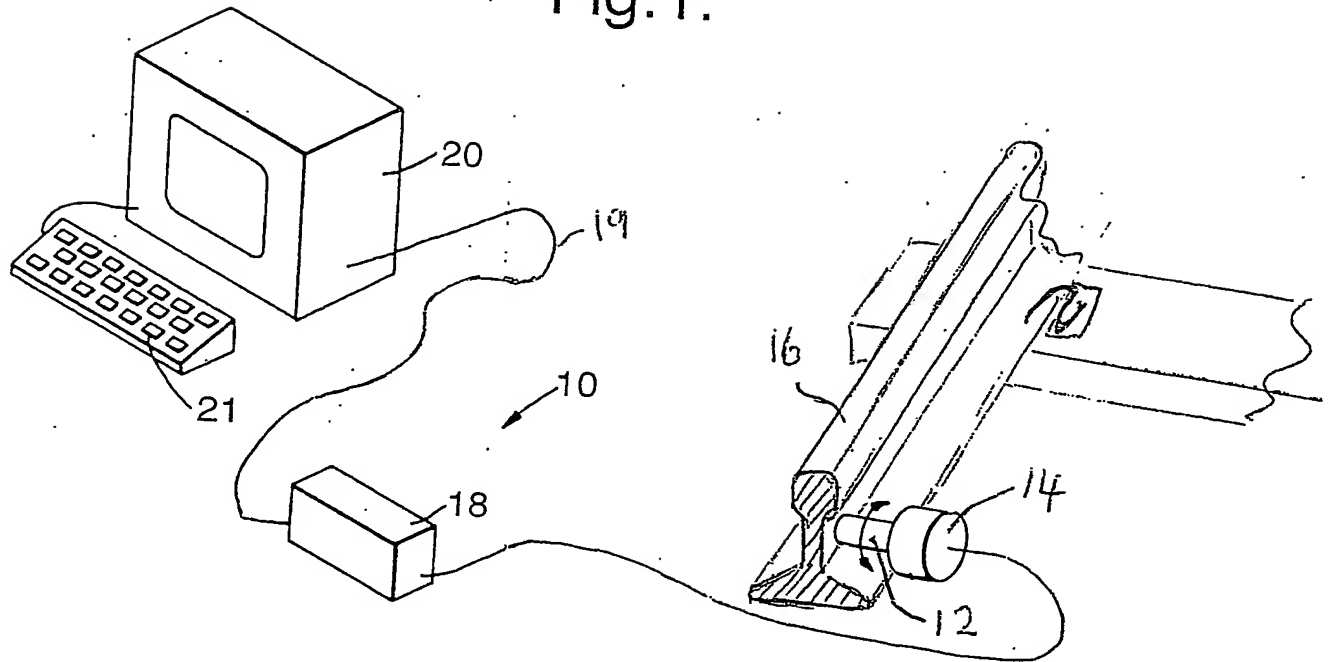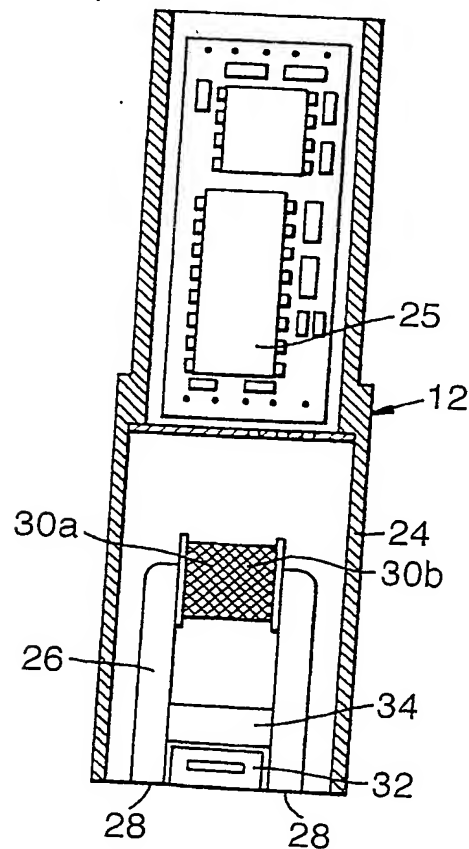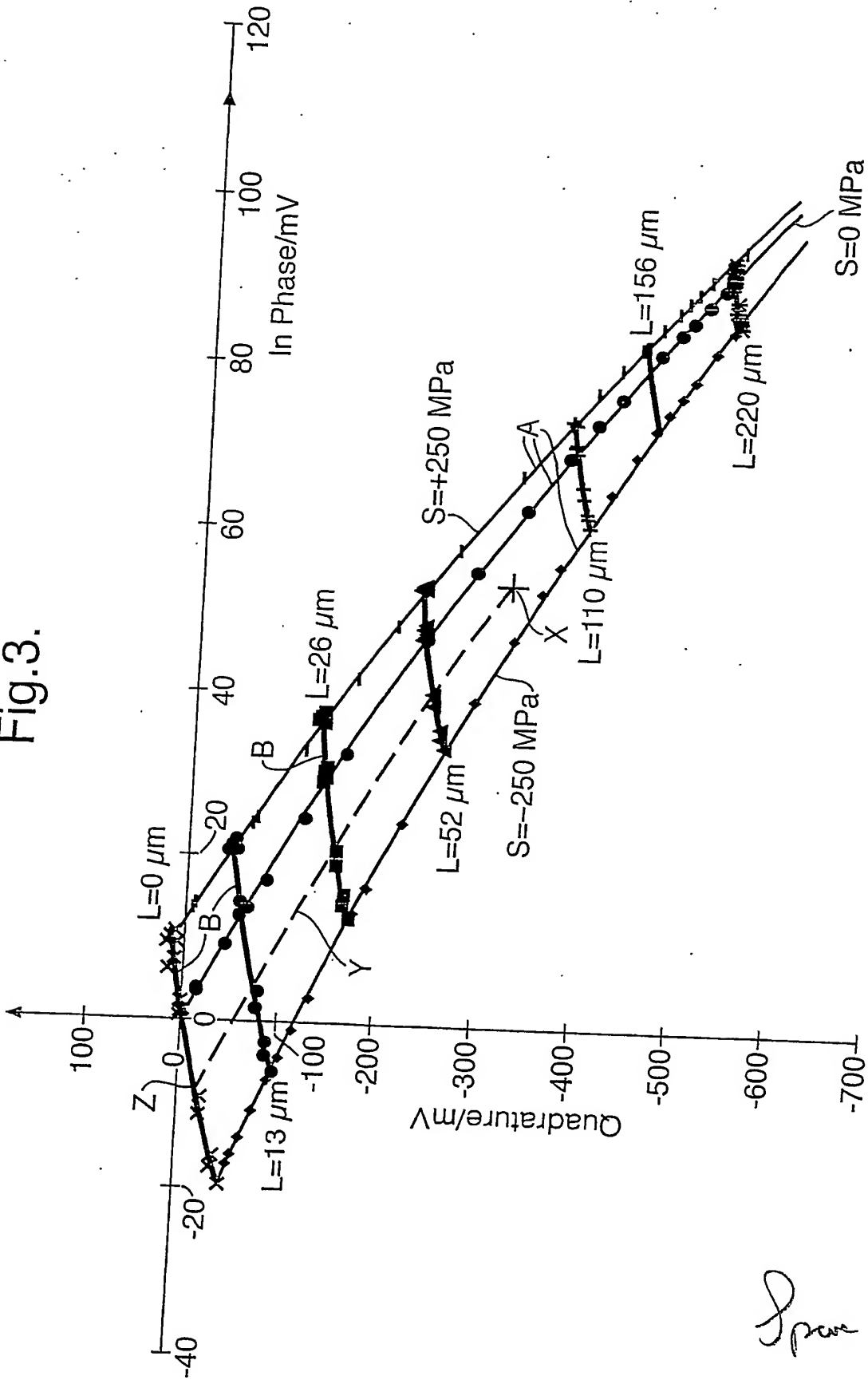*f) For details of the fee and ways to pay please contact the Patent Office.*
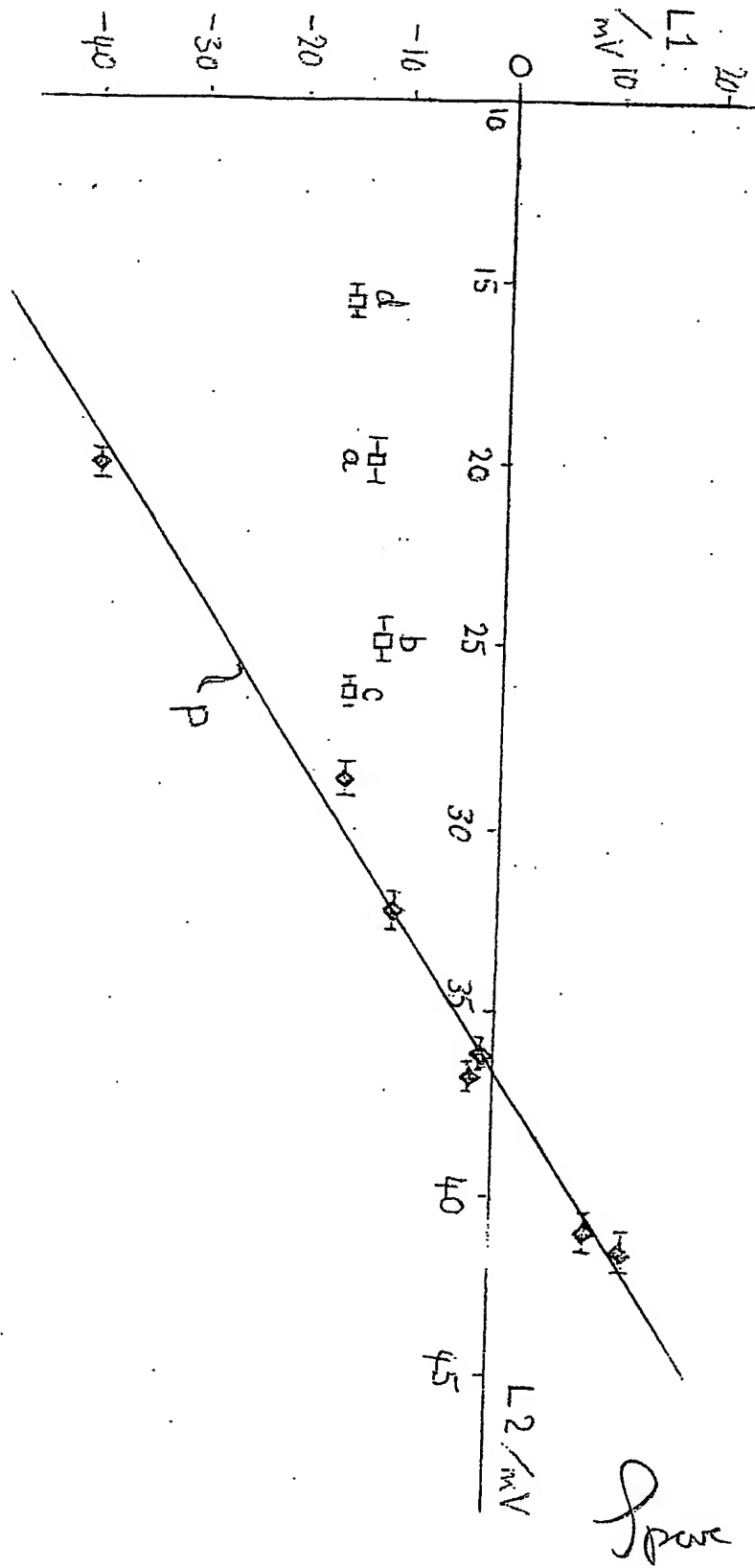
Fig.1.

Fig.2.

MdCm

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Fig.3.

Fig. 4

L1
/mV 10

20

10

0

-10

-20

-30

-40

15 d

20 a

25 b

c

30

35

40

45

P

L2/mV

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MdCm

Measurement of thermally induced stress

This invention relates to a method and apparatus for determining thermally induced stress in a ferromagnetic
5 object such as a rail of a railway line, using an electromagnetic probe.

The stresses in structures such as rails, bridges and pipelines, complex mechanisms such as vehicles and
10 machinery, or simple devices such as struts, cables or bearings arise from various causes including changes of temperature, and the loads and pressures due to use. There may also be residual stresses arising from the fabrication of the structure or device, and any bending
15 that the structure or device was subjected to during construction; the residual stresses arising from fabrication will also be affected by any stress-relieving heat treatment. A way of measuring stress in a steel plate is described in US 5 828 211 (GB 2 278 450), this
20 method using a probe containing an electromagnetic core to generate an alternating magnetic field in the plate, and then combining measurements from two sensors, one being a measure of stress-induced magnetic anisotropy (SMA), and the other being a measure of directional
25 effective permeability (DEP). The probe is gradually turned around so the magnetic field has a plurality of different orientations in the plate, and these measurements are taken at each such orientation. The probe enables the stress to be measured near the surface,
30 the depth of penetration depending upon the frequency.

In the case of railway lines, thermally-induced stresses are a contributing factor for both rail breaks (when the rail temperature falls, for example in winter),
35 and for rail buckling (when the rail temperature rises, for example in summer). Traditionally in continuous-

welded rail these problems are minimised by initially
installing the rail in a state of tension, such that the
thermal stresses would become zero if the rail
temperature were to rise to a "stress-free temperature"
5   which is selected such that in practice the thermal
stresses do not reach excessive values. It would be
desirable to be able to monitor the thermally-induced
stresses in a rail, but this is no simple matter. As a
rule, stress measurement techniques measure the total
10   stress, which is the sum of the thermally-induced stress
and the residual stress (as tensors); to determine the
thermal stress it is therefore necessary to also
ascertain the residual stress. This can be measured by
measurements on a rail that is unconstrained, for example
15   by cutting out a section of rail, but a nondestructive
measurement technique would be desirable.

It will also be appreciated that accurate
measurement of rail temperature is also very difficult to
20   achieve, because of varying environmental conditions
along a length of rail and because of the comparatively
poor thermal conductivity of rail steel; an uncertainty
in the mean temperature of any less than about +/- 2°C
would be difficult to achieve. Temperature measurements
25   in sunshine are likely to be even harder.

According to the present invention there is provided
a method for determining the residual stress and the
thermally-induced stress in a rail, the method comprising
30   measuring, using at least one electromagnetic probe, the
stresses in part of the rail remote from the railhead in
a direction perpendicular to the longitudinal axis of the
rail, and in a direction parallel to the longitudinal
axis, determining from the stress in the perpendicular
35   direction an estimate of the residual stress in the
parallel direction, and hence by comparing the measured

stress in the parallel direction to the estimated residual stress in the parallel direction determining the thermally-induced stress.

5   It has been discovered that residual stresses in rails vary from rail to rail, and through the life of a rail. However the lifetime variation can be minimised by considering stresses in regions remote from the railhead, that is to say in the web or possibly the foot of the

10   rail. The residual stresses in both the parallel and perpendicular directions are principally caused by the straightening which is the final stage of manufacture of the rail, and consequently can be related to each other. In the web, for example, the residual stresses are

15   typically compressive, in the region 120 to 220 MPa in the parallel direction, and 50 to 100 MPa in the perpendicular (vertical) direction. It should be appreciated that the variations in thermally-induced stress in the parallel direction are only about 2.4

20   MPa/°C, so that variations in the residual longitudinal stress arising from the manufacturing process of say 50 MPa are generally much larger than the thermally-induced stresses.

25   In the preferred stress-measurement method the or each probe comprises an electromagnet means, means to generate an alternating magnetic field in the electromagnet means and consequently in the object, and a magnetic sensor arranged to sense a magnetic field due to

30   the electromagnet means; and the method comprises resolving signals from the magnetic sensor into an in-phase component and a quadrature component; mapping the in-phase and quadrature components directly into stress and lift-off components; and deducing the stress from the

35   stress component so determined.

The mapping requires a preliminary calibration, with a specimen of the material, to determine how the in-phase and quadrature components of the signal vary with lift-off (at a constant stress) and vary with stress (at a

5   constant lift-off), and deducing from the calibration measurements the applicable mapping for any stress and any lift-off. The mapping may be represented in the impedance plane (i.e. on a graph of quadrature component against in-phase component) as two sets of contours

10   representing signal variation with lift-off (for different values of stress) and signal variation with stress (for different values of lift-off), the contours of both sets being curved. The contours of one set intersect the contours of the other set at non-orthogonal

15   angles. Surprisingly it has been found that the angles at which the constant lift-off contours intersect any one contour of constant stress are all the same. Hence measurements taken along a few contours of each set enable the positions of the other contours of each set to

20   be determined. This method of interpreting the signals and distinguishing between stress and lift-off is described in detail in pending patent application PCT/2002/004531.

25   Surprisingly this simple mapping has been found to give an accurate representation of the variation of the signals with material property (e.g. stress), and provides a simple way to distinguish these variations from variations arising from lift-off or other

30   geometrical variations such as surface texture or curvature.

Preferably the electromagnet means comprises an electromagnetic core and two spaced apart electromagnetic

35   poles, and the magnetic sensor is preferably arranged to sense the reluctance (or flux-linkage) of that part of

the magnetic circuit between the poles of the electromagnet means. It is also desirable to arrange for such measurements to be taken with a plurality of different orientations of the magnetic field, at a single
5   location on the object. This may be achieved using a single probe that is rotated at that location, measurements being taken with different orientations of the probe, or using an array of probes of different orientations that are successively moved to that
10 location. In either case, the sensor or sensors provide a measure of the permeability of the material through which the flux passes between the poles; the corresponding measurements at different probe orientations at a location on the object hence indicate
15 the effective permeability in different directions.

The probe, or at least some of the probes, may also include a second magnetic sensor between the two poles and arranged to sense magnetic flux density perpendicular
20 to the direction of the free space magnetic field between the poles. This second sensor would detect no signal if the material were exactly isotropic; however stress induces anisotropy into the magnetic properties of the material, and so the signals received by the second
25 sensor (or flux-rotation sensor) are a measure of this stress-induced magnetic anisotropy. The variations in the flux rotation signals at different probe orientations, at a location on the object, enable the directions of the principal stress axes to be accurately
30 determined. The flux rotation signals can also be related to the stress.

The probe, or at least some of the probes, may also include a third magnetic sensor (a flux-leakage sensor)
35 between the poles arranged to sense magnetic flux density parallel to the free space magnetic field. This third

sensor detects flux leakage which is influenced by changes in material properties, lift-off, and cracks. As with the flux-linkage sensor, measurements at a location are preferably made at different probe orientations.

5

The reluctance (or flux-linkage) signal from the or each probe is preferably backed-off, i.e. processed by first subtracting a signal equal to the signal from that sensor with the probe adjacent to a stress-free location.

10 The backed-off signal is then amplified so the small changes due to stress are easier to detect. This backing off is performed after resolving into in-phase and quadrature components but before performing the mapping. Preferably the signals from the or each probe are

15 digitized initially, and the backing-off and resolution are performed by analysis of the digital signals.

Generally, the more different probe orientations are used for taking measurements the more accurate the

20 determination of stress levels can be.

The invention will now be further and more particularly described, by way of example only, and with reference to the accompanying drawings, in which:

25

Figure 1 shows a diagrammatic view of an apparatus for measuring stress;

Figure 2 shows a longitudinal sectional view of a

30 probe for use in the apparatus of figure 1;

Figure 3 shows graphically the variation of the backed-off quadrature and in-phase components of flux linkage with variations of lift-off, and with variations

35 of stress; and

Figure 4 shows graphically the correlation between the signals representing stress in the vertical and longitudinal directions in a rail web.

5   Referring to figure 1, a stress measuring apparatus 10 includes a sensor probe 12 comprising sensors for flux-linkage, flux-rotation and flux-leakage, the probe 12 being attached to an electric motor 14 which can be held by an operator, so the motor 14 can turn the probe 10   12 with one end adjacent to a surface of a steel object 16 (the web of a rail in this case) in which the stresses are to be determined. The sensor probe 12 and motor 14 are connected by a 2 m long umbilical cable 17 to a signal conditioning/probe driver unit 18. The unit 18 is 15   connected by a long umbilical cable 19 (which may for example be up to 300 m long) to an interface unit within a microcomputer 20, which has a keyboard 21. Operation of the apparatus 10 is controlled by software in the microcomputer 20.

20

Referring now to figure 2, the probe 12 is shown detached from the motor 14, in longitudinal section although with the internal components shown in elevation (the connecting wires within the probe 12 are not shown). 25   The probe 12 comprises a cylindrical brass casing 24 of external diameter 16.5 mm and of overall height 60 mm, the upper half being of reduced diameter whereby the probe 12 is attached to the motor 14. The upper half of the casing 24 encloses a head amplifies 25. The lower 30   half encloses a U-core 26 of laminated mu-metal (a high permeability nickel/iron/copper alloy) whose poles 28 are separated by a gap 7.5 mm wide, and are each of width 2.5 mm, and of thickness 10 mm (out of the plane of the figure). The poles 28 are in the plane of the lower end 35   of the casing 24, which is open. Around the upper end of the U-core 26 is a former on which are wound two

superimposed coils 30.   One coil 30a (which has 200
turns) is supplied with the sinusoidal drive current from
the unit 18; the other coil 30b (which has 70 turns)
provides flux linkage signals.

5

Between the two poles 28 is a former on which is
wound a 1670-turn rectangular coil 32, about 4 mm high
and 6 mm wide, and 6 mm-square as seen from below, the
windings lying parallel to the plane of the figure so the
10 longitudinal axis of the coil 32 is perpendicular to the
line between the centres of the poles 28.   The coil 32 is
supported by a support plate 34 fixed between the arms of
the U-core 26 so the lower face of the coil 32 is in the
plane of the poles 28.   The coil 32 provides the flux-
15 rotation signals.   If a flux-leakage signal is required,
a coil may be wound on the same former but with windings
perpendicular to the plane of the figure.   All the
signals are amplified by the head amplifier 25 before
transmission to the unit 18.

20

In operation of the system 10, the motor 14 is
supported so the lower end of the probe 12 is adjacent to
the surface of a steel object and the longitudinal axis
of the probe 12 is normal to the surface.   An alternating
25 current of the desired frequency and amplitude is
supplied to the drive coil 30a, so the magnetic field in
the object 16 oscillates about zero with an amplitude
much less than saturation.   To set up the system 10,
measurements are first made using an object of the same
30 type of steel as the rail 16 but in which the stresses
are negligible. The in-phase and quadrature components of
the flux linkage signal (i.e. the component in phase with
the drive current, and the component differing in phase
by 90°) received by the microcomputer 20 are each backed
35 off to zero, and the backing off values are then fixed.
During all subsequent measurements the flux linkage

components are backed off by these same amounts (i.e. subtracting a signal equal to the component observed at a stress-free location).

5   Stress measurements can be taken by placing the probe 12 adjacent to the web of the rail 16. The orientation of the line joining the centres of the poles 28 (referred to as the orientation of the probe 12) is noted relative to a fixed direction on the surface. The
10 motor 14 is then energized to rotate the probe 12, for example in a step-wise fashion 10° at a time through a total angle of 360°. At each orientation of the probe 12 all the signals are measured.

15   It will be appreciated that the procedure of the invention is applicable with many different probes. The probe 12 might for example be modified by using a U-core 26 of a different material such as silicon iron (which can provide higher magnetic fields), or indeed the drive
20 coil might be air-cored. The probe might be of a different shape or size; probes ranging in size between about 3 mm and 75 mm have been used for different purposes.

25   The flux rotation signals vary sinusoidally with probe orientation, so the orientation at which they have their maxima and minima can be determined. The directions midway between these two orientations are the directions of the principal stress axes. Measurements of
30 flux rotation are therefore useful if the principal stress directions are unknown. The values of flux linkage and flux leakage also vary sinusoidally with probe orientation (in antiphase with eachother), and the values are observed at the principal stress directions. If the
35 principal stress directions are already known, then the probe 12 might instead be merely oriented to those

directions, and the measurements made; no rotation of the probe 12 would be necessary.

5   The values of the stresses in the web in the vertical and longitudinal directions can be determined from the experimental measurements of flux linkage with the probe 12 oriented in those directions. This requires calibration of the apparatus 10, taking measurements on a sample of material of the same type as that of the rail

10 16, while subjecting it to a variety of different stresses. This may be done with a rectangular strip sample in a test rig, flux linkage measurements being made at the centre of the sample where the principal stress direction is aligned with the axis of the test

15 rig. Referring to figure 3 this shows the backed-off flux-linkage in-phase and quadrature components obtained in such a test rig, the measurements being made with a drive frequency of 70 Hz, and the specimen being a steel bar. A first set of measurements were made at

20 progressively larger values of lift-off, L, but with no stress, S. This gives the lift-off contour A, the lift-off varying between 0 and 220 μm. Similar lift-off contours A are obtained for other fixed values of stress, those for S = 250 MPa tension and compression being

25 shown. Measurements were then made at a range of different fixed values of lift-off, L, with varying stresses, S (both compression and tension), providing the contours B.

30   It will be appreciated that the contours A are curved, and the contours B are not orthogonal to the contours A, but that they intersect at substantially constant angles along any one lift-off contour A. Consequently it is only necessary to make calibration

35 measurements sufficient to plot a few such contours A and B, and the shapes of the other contours can be predicted.

After calibrating the probe 12 in this manner, measurements of stress can be readily made from observations of flux linkage signals (resolved and backed

5 off); as the contours enable the changes due to lift-off to be readily distinguished from changes due to stress. Any particular position in the impedance plane (i.e. in the graph of quadrature against in-phase components) corresponds to a particular value of stress and a

10 particular value of lift-off. The mapping between (in-phase, quadrature) coordinates and (stress, lift-off) coordinates may be carried out graphically, referring to such contours, or by calculation. For example if the flux linkage signal has the in-phase and quadrature

15 components of the position marked X, this corresponds to a lift-off of about 80 μm and a stress of about 125 MPa. Alternatively this value X may be translated (along the broken line Y) along a contour A of constant stress to find the in-phase and quadrature components at position Z

20 that would be obtained with zero lift-off.

The value of stress found in this way is, it will be appreciated, the uniaxial stress that would provide that value of the flux linkage signal. If the stresses are

25 actually biaxial, then a further calibration must be carried out with a cross-shaped sample in a test rig, flux linkage measurements being made at the centre of the sample where the principal stress directions are aligned with the axes of the test rig. Hence a graph or map may

30 be obtained for a range of values of stress on one axis (say the x-axis) and for a range of values of stress in the other axis (say the y-axis), with contours each of which shows the values of biaxial stress that give a particular value of apparent uniaxial stress along the x-

35 axis; and a similar graph may be obtained with contours showing values of biaxial stress that give a particular

value of apparent uniaxial stress along the y-axis.
Hence from measurements of apparent uniaxial stress along
the two principal stress axes obtained as described
earlier, the biaxial stress can be determined.

5

It will again be appreciated that the biaxial stress
may be determined either graphically or by calculation in
this way. Apparent values of uniaxial stress (in MPa)
may be used for this purpose, or alternatively the

10 numerical value of the flux linkage signal (in mV),
either the in-phase or quadrature value, obtained by
eliminating the effect of lift-off as described in
relation to figure 3, may be used. Although the above
method of correcting for lift-off has been described in

15 relation to flux-linkage signals it is equally applicable
to flux-leakage signals.

In the case of rail steels it has been found that
the signals, if corrected for lift-off (for example as

20 described above), both those for flux-linkage and those
for flux-leakage, can be related almost linearly to the
stress. (It will be appreciated that the flux-leakage
signals increase as the flux-linkage signal decrease.)
Measurements have been taken on seven different rails, on

25 cut sections so that there is no thermal stress; each
section of rail was 3 m long, and all the measurements
were taken more than 0.3 m from either end to avoid those
regions in which the residual stresses may have relaxed.
There has been found to be a clear positive correlation

30 between the signals in the longitudinal and vertical
directions, and so between the stresses in the
longitudinal and vertical directions.

Referring now to figure 4, this shows graphically
35 the flux leakage signal in the vertical direction (L1)
and the flux leakage signal in the longitudinal direction

(L2), each signal having been corrected for lift-off, the black diamonds showing the mean values for the seven different rail specimens. The positive correlation is clearly evident, and the straight line graph P may be
5 represented by the equation:

$$L1 = 2.27\ L2\ -\ 83.6$$

This experimentally-observed relationship between
10 the vertical and longitudinal flux-leakage signals corresponds to a linear relationship between the vertical and longitudinal residual stresses. By measuring the stress in the vertical direction in a rail that is in situ (and in which there therefore may be thermally-
15 induced stresses), this relationship enables the residual stress in the longitudinal direction to be determined. The difference between this and the observed total stress in the longitudinal direction consequently represents the thermally-induced stress.
20

The white squares on the graph show measurements made on a single rail in situ at different stages during cutting and rewelding: a is the initial measurement on the rail in situ; b is after cutting the rail, but with
25 the clips still in place; c is after cutting and unclipping the rail; and d is after rewelding the rail and replacing the clips. At c one would expect that there should be no thermally-induced stress (so that the displacement of this point from the straight-line graph P
30 suggests some instrumentation error). Nevertheless it is clear that the signals L1 representing vertical stresses vary only slightly during this process, whereas the signals L2 representing longitudinal stresses get closer to the stress-free state when the rail is cut and then
35 unclipped (b and c), as the thermally-induced stress is removed, and then get further from the stress-free state

when the rail is rewelded (d).

The measurements (a) made with the rail in situ can also be compared with measurements by a mechanical technique (referred to as Verse, and involving unclipping a section of rail, and measuring the force needed to pull it up). In this case the thermally-induced longitudinal stress calculated as described above from the measurements of leakage-flux was 53 MPa at an ambient temperature of 12.2°C; assuming the longitudinal stress changes by 2.4 MPa/°C, this indicates that the thermally-induced longitudinal stress would become zero at 34.3°C. By comparison, the figure obtained using the Verse technique was 31°C.

Claims

1. A method for determining the residual stress and the thermally-induced stress in a rail, the method comprising measuring, using at least one electromagnetic probe, the stresses in part of the rail remote from the railhead in a direction perpendicular to the longitudinal axis of the rail, and in a direction parallel to the longitudinal axis, determining from the stress in the perpendicular direction an estimate of the residual stress in the parallel direction, and hence by comparing the measured stress in the parallel direction to the estimated residual stress in the parallel direction determining the thermally-induced stress.

2. A method as claimed in claim 1 wherein the stresses are measured in the vertical and longitudinal directions in the web of the rail.

3. A method as claimed in claim 1 or claim 2 wherein the electromagnetic probe comprises an electromagnet means comprises an electromagnetic core and two spaced apart electromagnetic poles, and at least one magnetic sensor arranged to sense either the reluctance of that part of the magnetic circuit between the poles of the electromagnet means, or flux-leakage between the poles of the electromagnet means.

4. A method as claimed in any one of the preceding claims wherein signals from that least one magnetic sensor are analysed into an in-phase component and a quadrature component, and these are mapped directly into material property and lift-off components.

5. A method as claimed in claim 4 wherein the mapping is represented in the impedance plane (i.e. on a graph of

quadrature component against in-phase component) as two
sets of contours representing signal variation with lift-
off (for different values of stress) and signal variation
with stress (for different values of lift-off), the
5   contours of both sets being curved.

6.   A method for determining the residual stress and the
thermally-induced stress in a rail, substantially as
hereinbefore described with reference to, and as shown
10   in, the accompanying drawings.

7.   An apparatus for determining the residual stress and
the thermally-induced stress in a rail by a method as
claimed in any one of the preceding claims.
15

15702 MdCm   P.T. Mansfield
                                        Chartered Patent Agent
                                        Agent for the Applicants
20

Abstract

Measurement of thermally induced stress

5   In a railway line, thermally-induced stresses are a
factor for both rail breaks and rail buckling. These
stresses are in the longitudinal direction. A
nondestructive measuring technique enables both the
residual stress and the thermally-induced stress in a
10   rail to be determined. An electromagnetic probe is used
to measure the stresses in the rail web in the vertical
direction, and in the direction parallel to the
longitudinal axis. The residual stress in the
longitudinal direction can be determined from the
15   measured stress in the vertical direction; hence the
thermally-induced stress can be deduced. (figure 4)

20   15702 MdCm